



# Improvements in GaSb Homoepitaxial and IMF Solar Cells Grown via Metal-Organic Chemical Vapor Deposition

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The narrow band gap (0.72 eV) of GaSb makes it a useful material for several applications

## Infrared Detectors



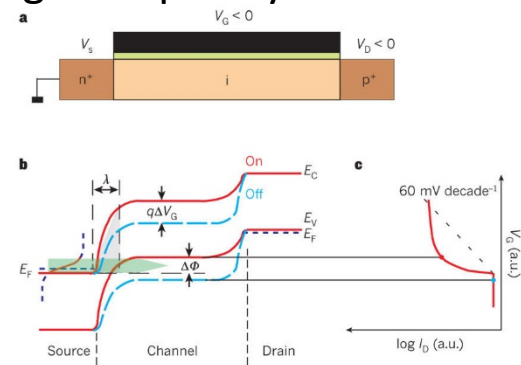
<https://dir.indiamart.com/impcat/infrared-detector.html>

## Infrared LEDs

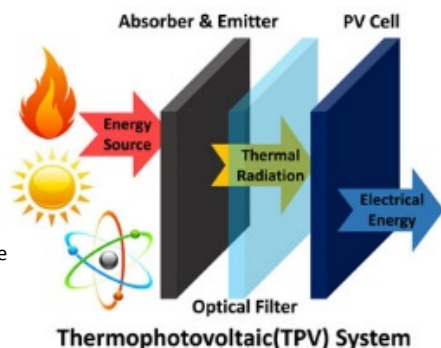


<https://storify.com/compactlighting/what-is-led-bulbs-and>

## High Frequency Transistors

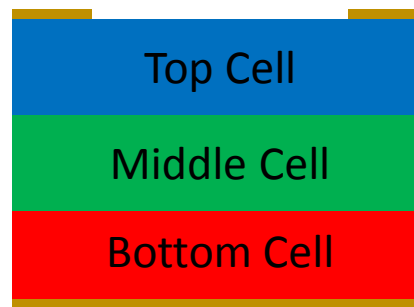


<http://www.nature.com/nature/journal/v479/n7373/full/nature10679.html>



<http://mel.khu.ac.kr/research/arch1.html>

## Thermophotovoltaics

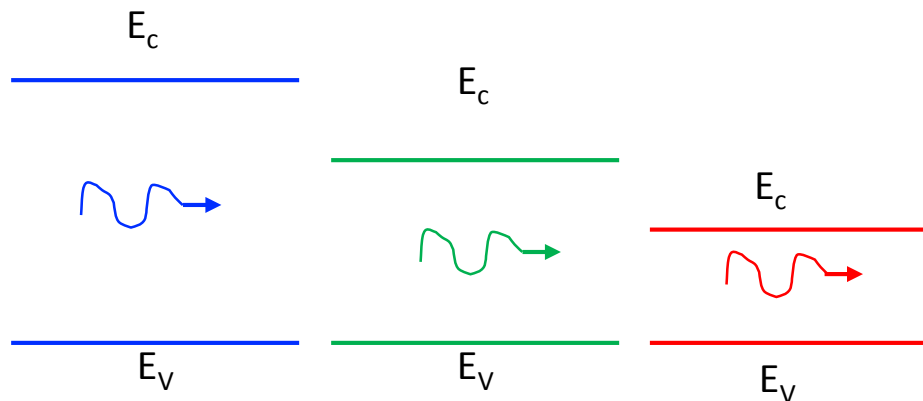
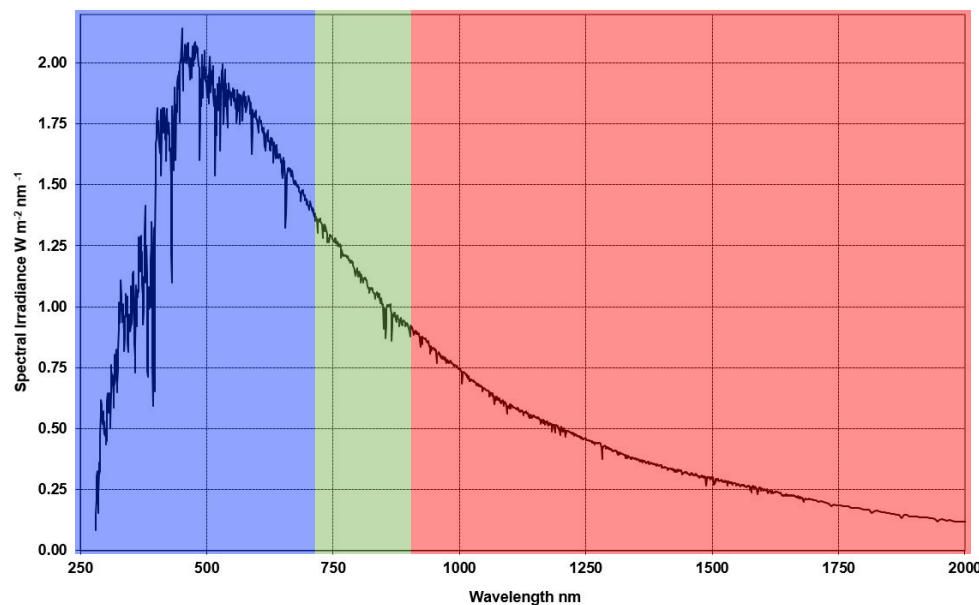


## Multi-junction Solar Cells

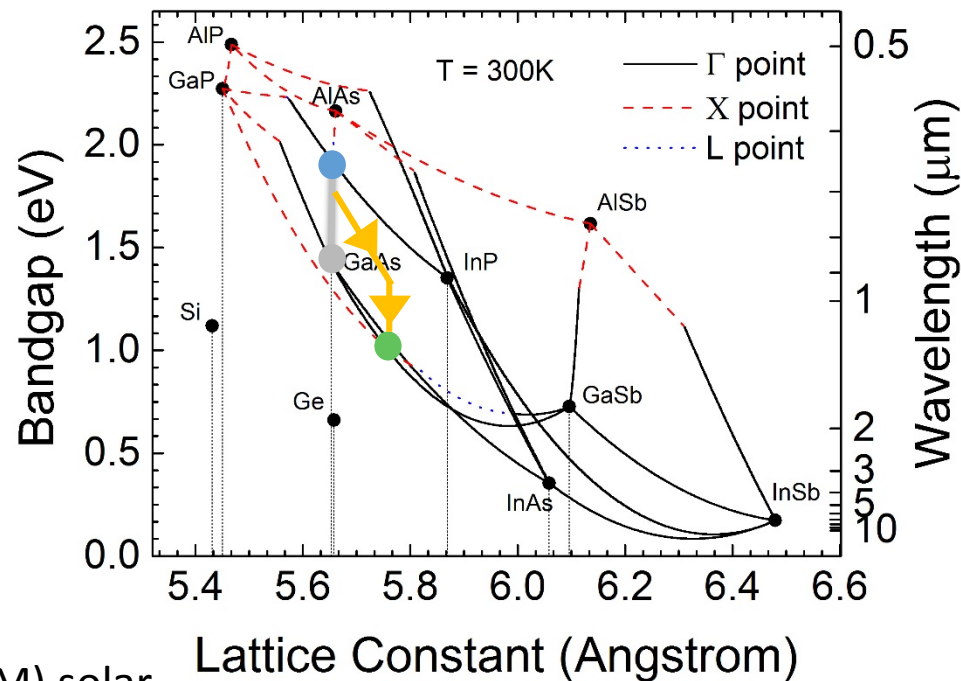
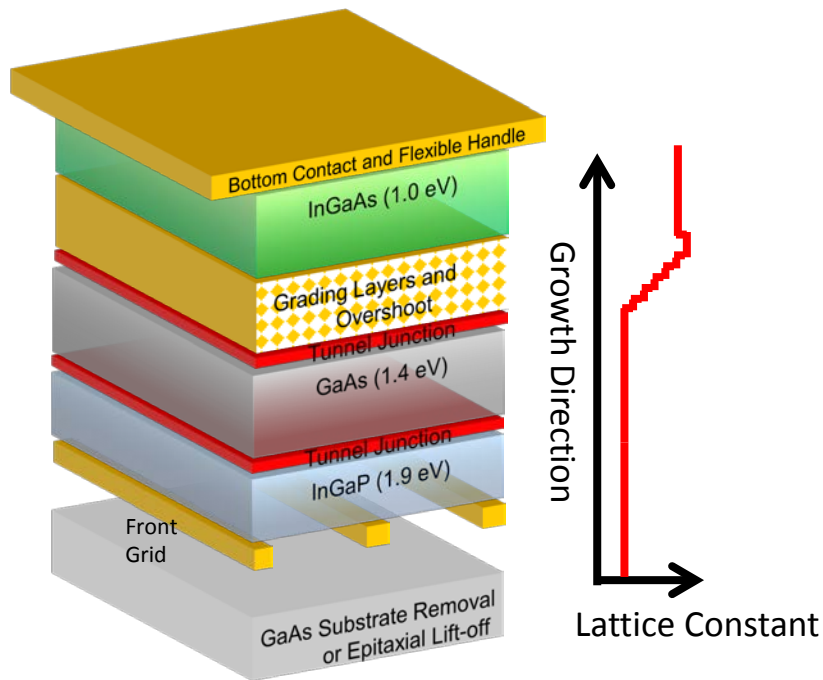
- **Single junction** solar cells are limited in percent of the solar spectrum they can absorb
  - GaAs ( $E_g=1.42$  eV,  $\lambda=873$  nm) collects light most efficiently between  $\sim 700$  and  $885$  nm
  - The two biggest loss mechanisms are **transmission below the bandgap** and **thermalization**
- **Multijunction** solar cells stack materials of varying bandgaps in order to collect more of the solar spectrum

This greatly reduces loss due to transmission, mitigates thermalization loss, and **drastically increases efficiency!**

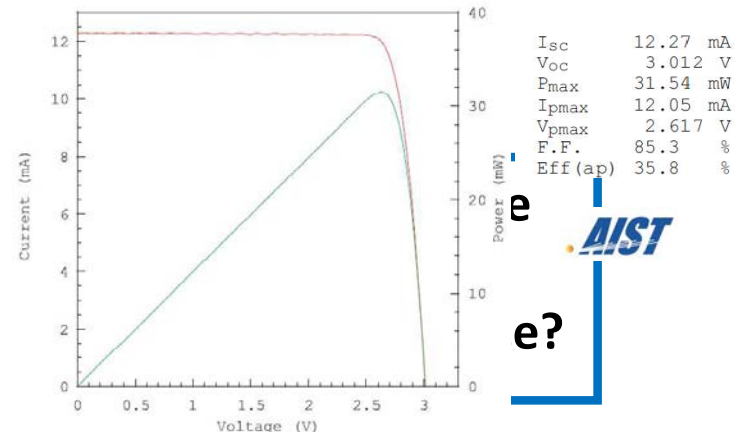
Air Mass 1.5 Solar Spectrum







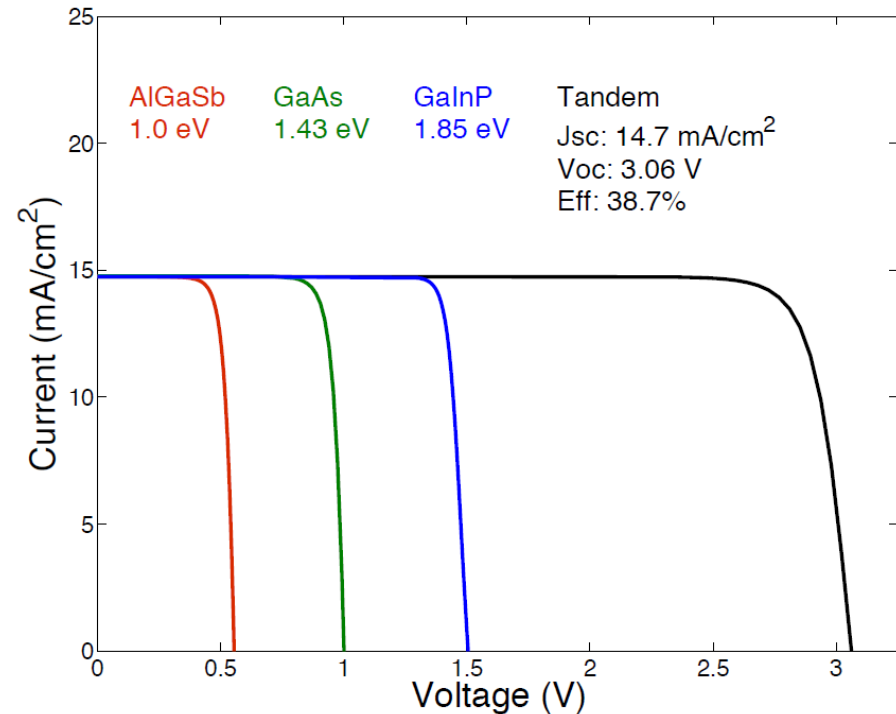
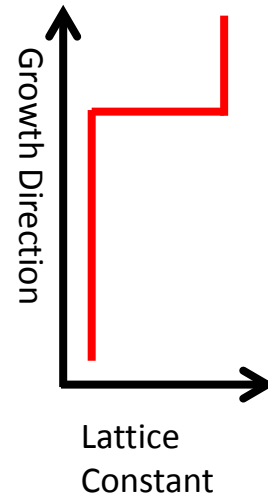
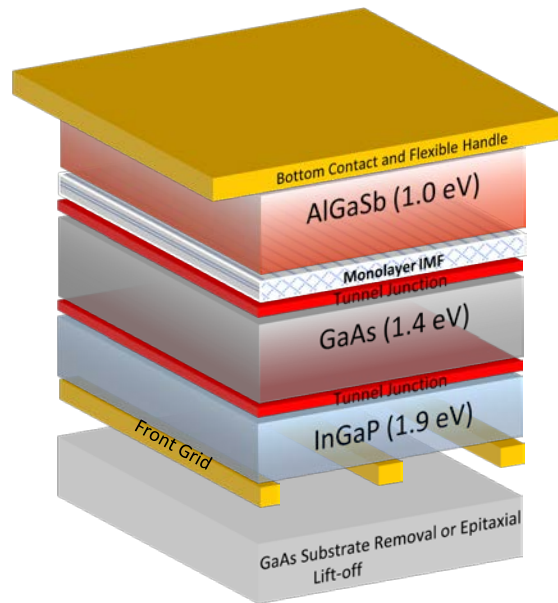
- **Inverted metamorphic multijunction (IMM)** solar cells have achieved efficiencies of 36%
- Requires several micron thick, growth intensive and expensive metamorphic buffer between GaAs and InGaAs
  - Buffer can have threading dislocation density on the order of  $10^6 \text{ cm}^{-2}$ , reducing minority carrier lifetimes
  - Attributes to **30%** of production cost



T. Takamoto et al. "World's highest efficiency triple-junction solar cells fabricated by inverted layers transfer process," in 2010 35th PVSC, 2010.



e?

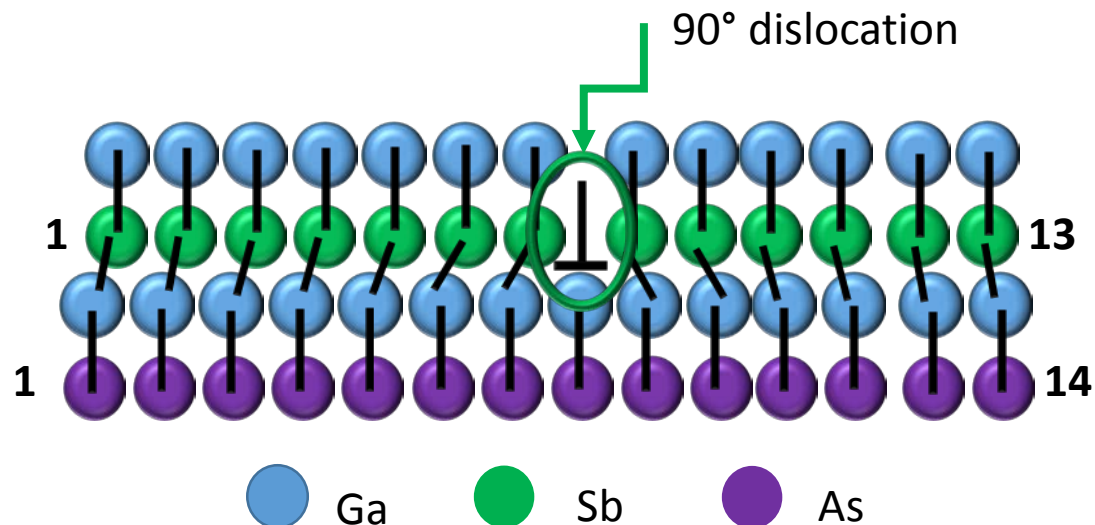


- AlGaSb ( $E_g=1.00$  eV) is proposed in place of InGaAs
- Like the IMM solar cell, this design is current matched and capable of achieving high efficiencies

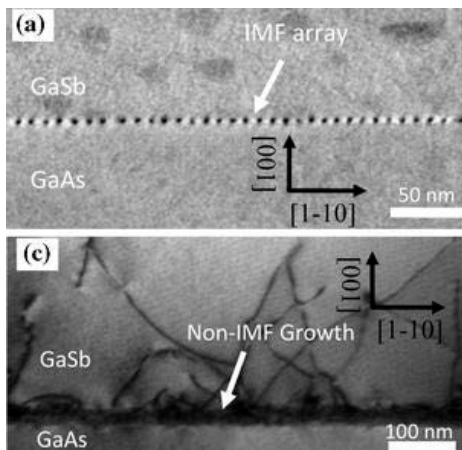
- There is a 7.5% lattice mismatch between AlGaSb and GaAs!

**How can we grow Sb based materials on GaAs?**

- By manipulating growth conditions at the GaAs-GaSb interface dislocations can be preferentially occur at  $90^\circ$  with a periodicity of GaSb:GaAs 13:14
  - Unlike a  $60^\circ$  threading dislocation, a  $90^\circ$  dislocation, or **misfit** dislocation, will not propagate up into the active layers of the device

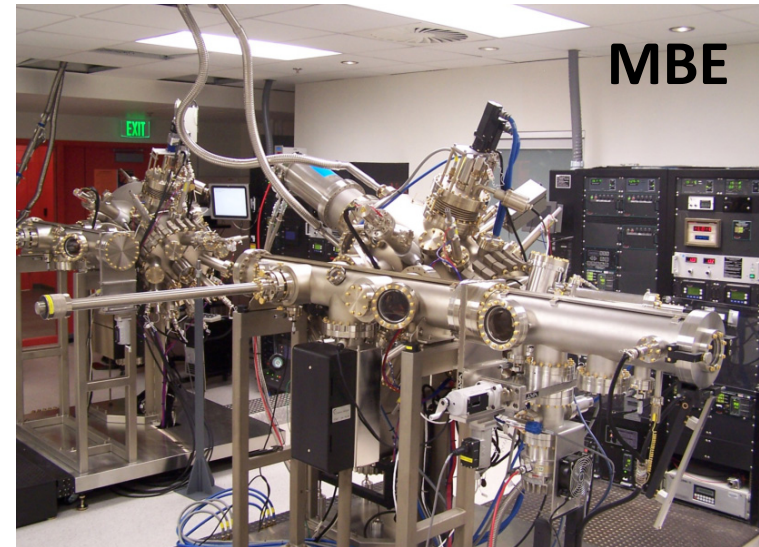


- Without this interfacial misfit, or **IMF** array, threading dislocation density (TDD) can reach as high as  $10^9 \text{ cm}^{-2}$
- High threading dislocation density has a strong impact on  $V_{OC}$  and minority carrier lifetime
- IMF has shown to be capable of TDD of  $10^5 \text{ cm}^{-2}$  and 98.5% relaxation



Jallipalli *et al.*, "Nanoscale Res Lett", vol. 4, no. 12, pp. 1458-1462, 2009

- The majority of research on the IMF technique has been done via molecular beam epitaxy (MBE)
  - MBE is a **very slow growth process** that requires ultra-high vacuum (slow throughput, intensive maintenance costs)
  - **This is not compatible with production!**



[http://www.seas.ucla.edu/~huffaker/research\\_mbe.html](http://www.seas.ucla.edu/~huffaker/research_mbe.html)



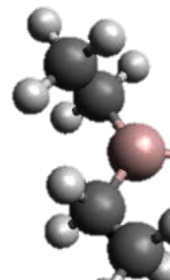
Aixtron 3x2" Close-Coupled Showerhead

- Here at RIT we have a metal organic chemical vapor deposition (MOCVD) system
  - MOCVD is capable of much higher growth rates and does not require ultra-high vacuum, making it **much more attractive for production**
  - Limited literature on the IMF technique via MOCVD provides many areas of study

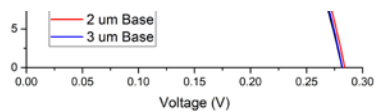
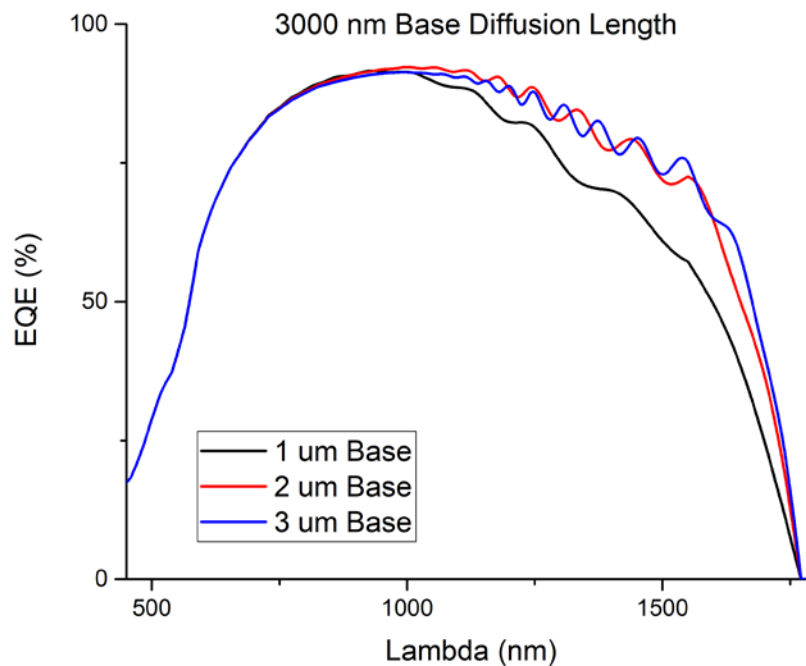
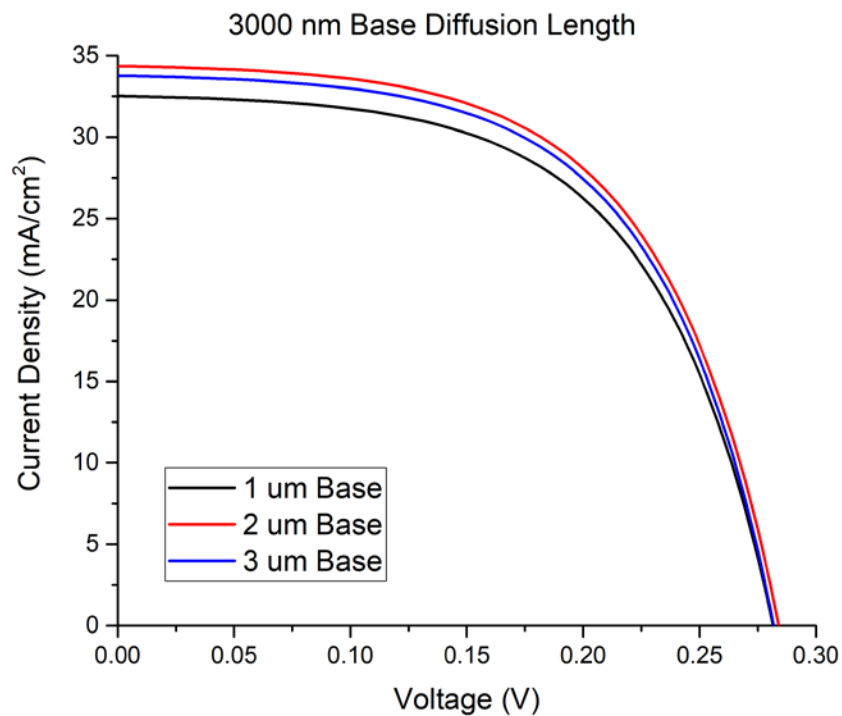


TEGa/TMSb

gallium  
n  
oping  
oother



TMGa/TMSb



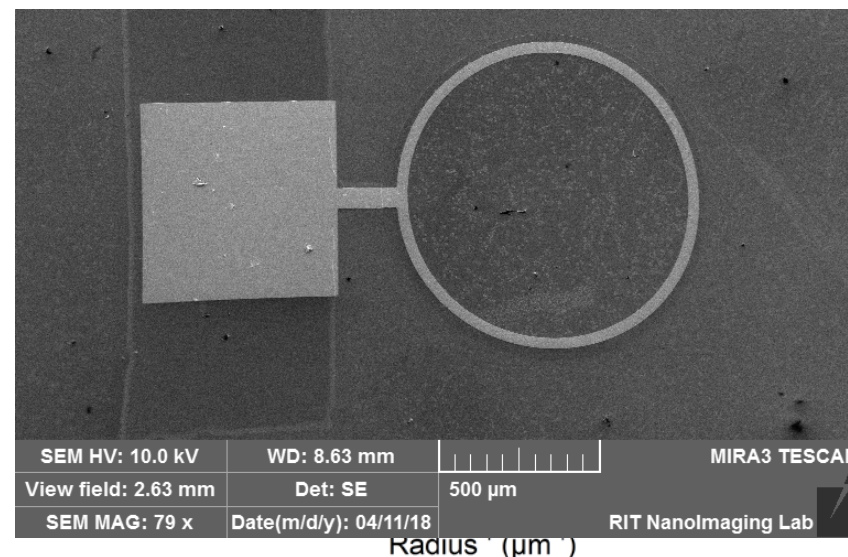
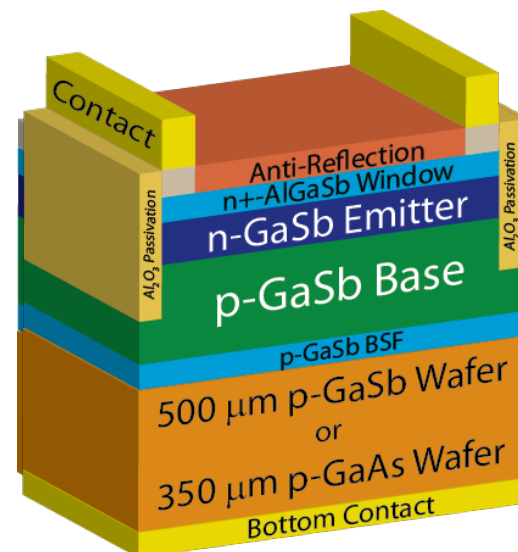
TESb/TEGa

TESb/TMGa

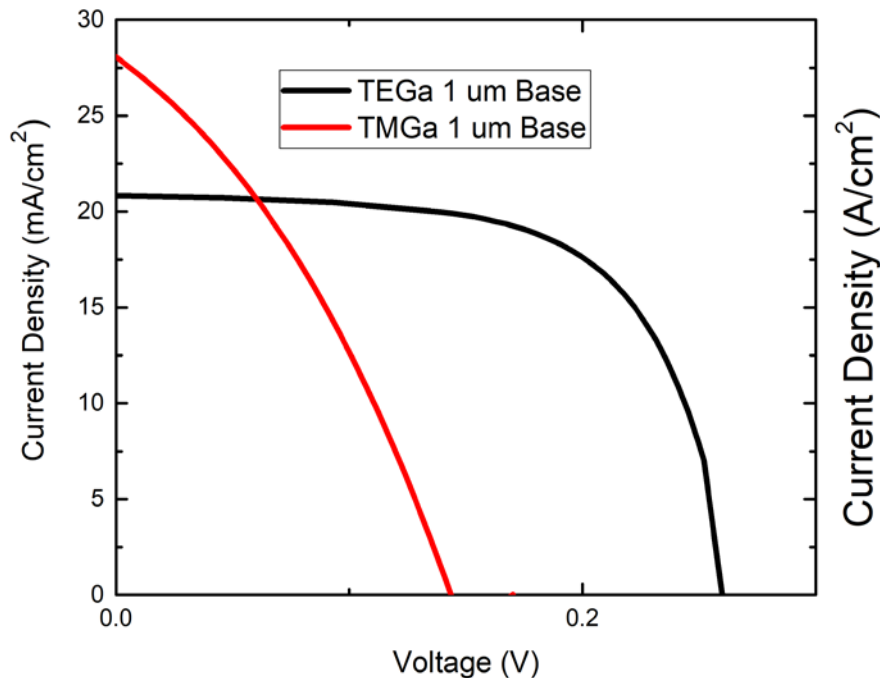
TESb/TMGa



- All devices were fabricated here in the RIT Semiconductor and Microsystems Fabrication Laboratory (SMFL)
- All devices are n-i-p
  - N-type emitter (hole minority carrier), P-type base (electron minority carrier)
- Devices are first mesa isolated using a Citric:HF:H<sub>2</sub>O<sub>2</sub> solution
- Device sidewalls are passivated using Al<sub>2</sub>O<sub>3</sub> deposited via atomic layer deposition (ALD)
  - This is done to mitigate the effect the GaSb native oxide has on device performance
  - **The timing and execution of this step is vital and has been heavily studied at RIT**
- Ti/Pt/Au is evaporated for the back ohmic contact, Ti/Au is evaporated for the front ohmic contact

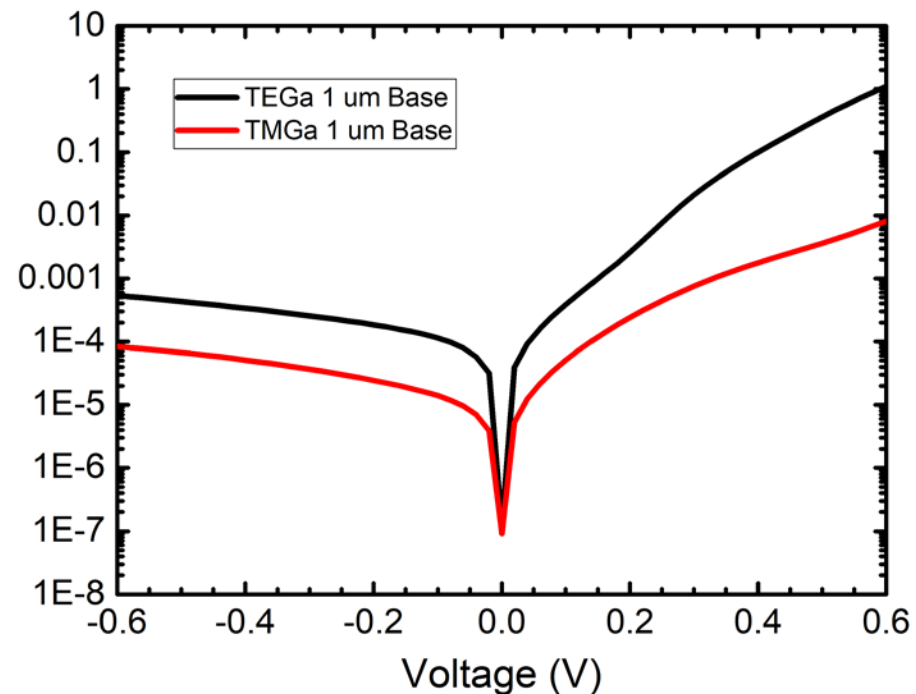


AM1.5 Illuminated IV



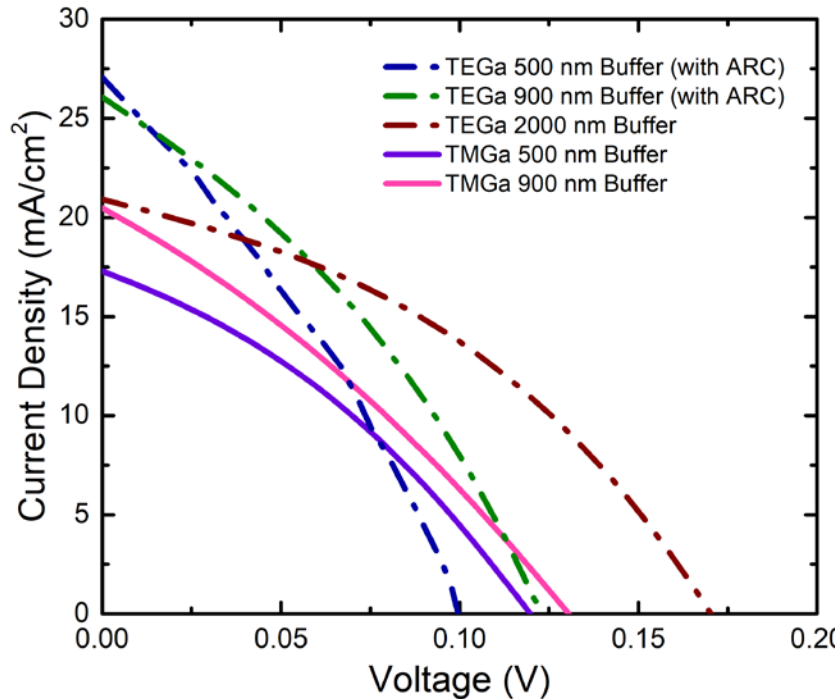
- For a triple junction solar cell with a GaSb bottom junction, target  $V_{OC} = 360$  mV
  - TEGa  $V_{OC} = 269$  mV
  - TMGa  $V_{OC} = 145$  mV
- Light IV measurements show heavy shunting in TMGa device
  - This is likely due to issues that occurred during fabrication

Dark IV

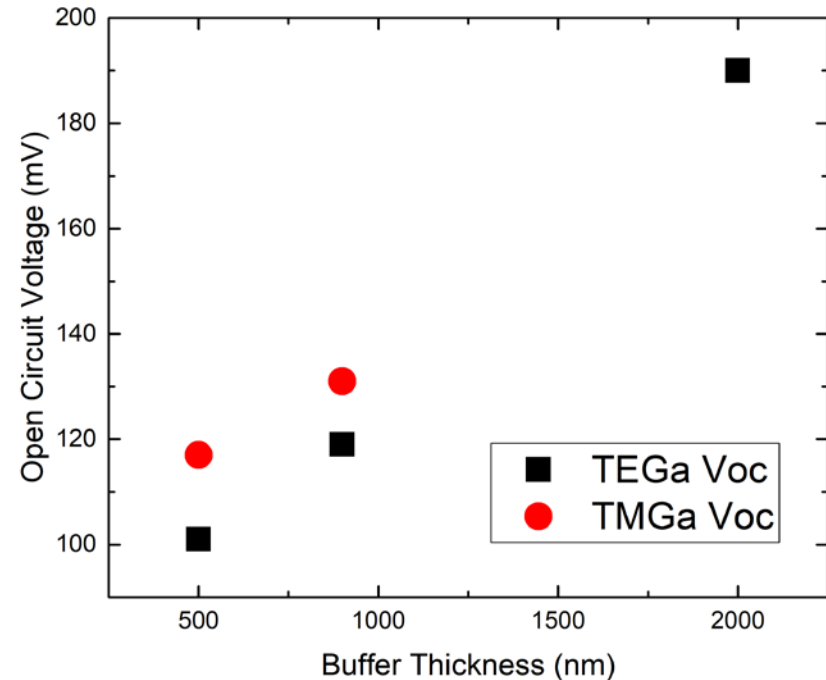


- Dark IV shows poor rectification of TMGa cell and a combination of poor series and shunt resistance
- Poor series resistance seen in fill factor (FF) of illuminated IV
  - TEGa FF = 53%
  - TMGa FF = 34%

AM1.5 Illuminated IV



- Light IV measurements show improved open circuit voltage ( $V_{oc}$ ) in TMGa devices for equivalent buffer thickness



- Dark IV shows that possibly better shunt resistance for TMGa, but **TMGa shows better open circuit voltage but worse series resistance in IMF devices**

$$j_p(\lambda) = qF_0(\lambda) \left\{ \frac{L_p F_1(\lambda) + \frac{S_p L_p}{D_p} F_2(\lambda) - F_3(\lambda) \left( \sinh \frac{d_1}{L_p} + \frac{S_p L_p}{D_p} \cosh \frac{d_1}{L_p} \right)}{\left( \cosh \frac{d_1}{L_p} + \frac{S_p L_p}{D_p} \sinh \frac{d_1}{L_p} \right)} - L_p F_4(\lambda) \right\}$$

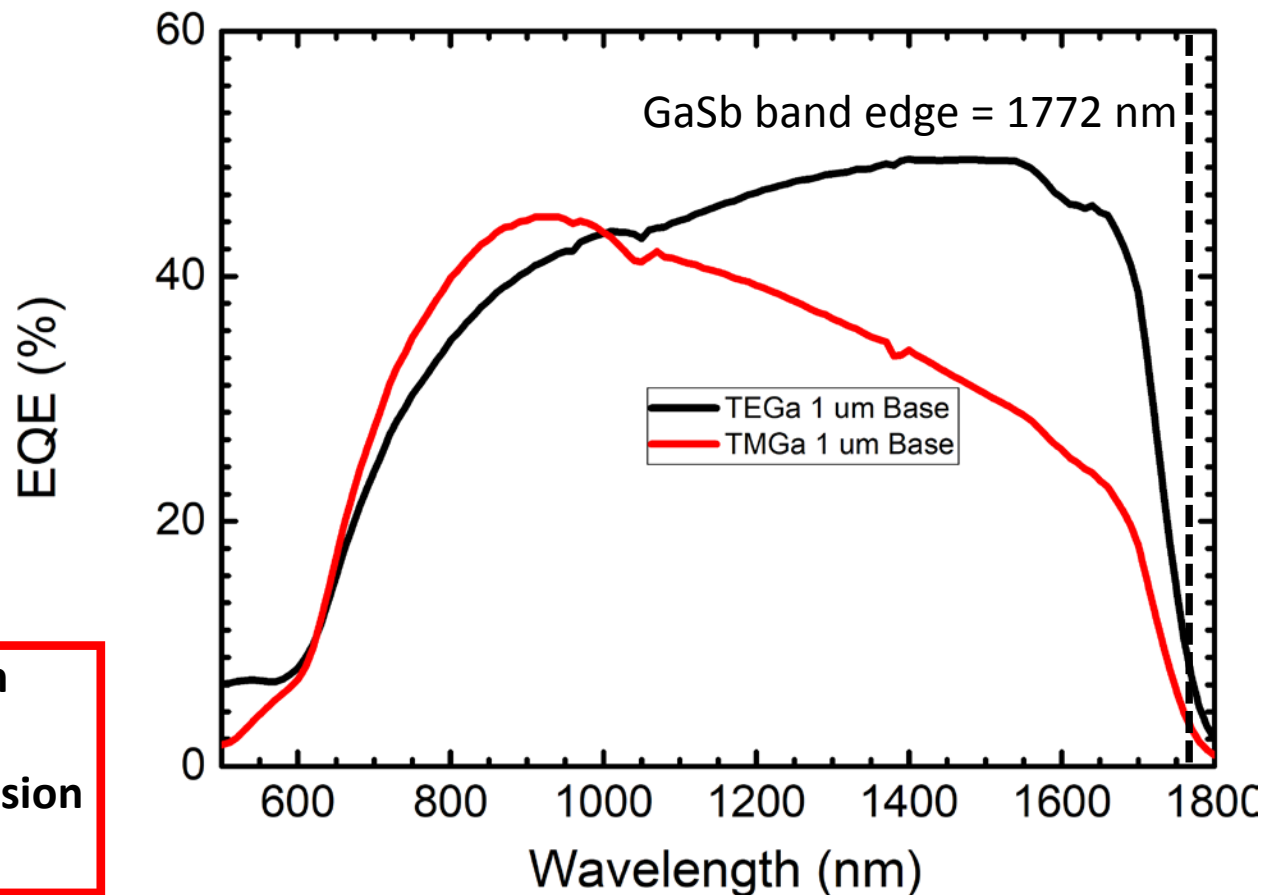
$$F_0(\lambda) = \frac{L_p (1 - R_1) \alpha \varphi_0}{(1 - \alpha^2 L_p^2)}, F_1(\lambda) = \alpha, F_2(\lambda) = 1, F_3(\lambda) = e^{-\alpha d_1}, F_4(\lambda) = \alpha e^{-\alpha d_1}$$

- Using an analytical drift-diffusion model (Hovel Model) for quantum efficiency the minority carrier diffusion lengths can be extracted
  - Above equation is for holes, by symmetry the equation for electrons is similar
- $L_{p/n}$  = Diffusion length
- $S_{p/n}$  = Recombination velocity
- $d$  = Thickness of the Quasi Neutral Region
- $D_{p/n}$  = Minority carrier diffusivity
- $R$  = Reflectance
- $\alpha$  = Absorption coefficient
- $\Phi$  = Photon flux



- External quantum efficiency (EQE) of TMGa cell is degraded compared to TEGa cell at  $\lambda > 1000$  nm
  - Indicative of degraded material quality in the base region
- Electrons not fully collected in TMGa base

**TEGa-Better base diffusion length**  
**TMGa-Better emitter diffusion length**



	$L_E$ (nm)	$L_B$ (nm)	$S_E$ (cm/s)	$S_B$ (cm/s)
TEGa	75	$\gg 3 \times$ base thickness	$\gg 10^6$	$\ll 10^6$
TMGa	196	600	$\gg 10^6$	$\ll 10^6$

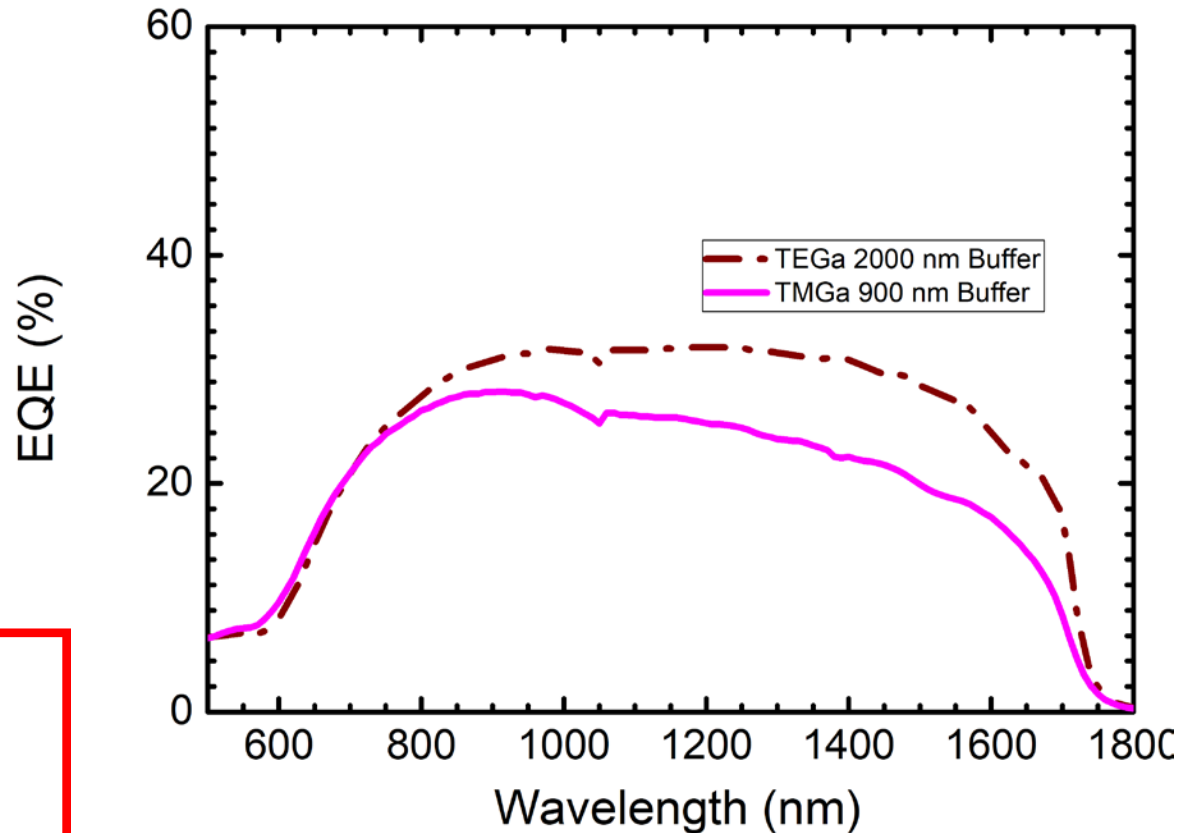
Emitter thickness=125 nm, n-type

Base thickness=1000 nm, p-type



- External quantum efficiency (EQE) of TMGa cell is degraded compared to TEGa cell in the same region as homoepitaxial cells, although they deviate a little earlier (800 nm)
- Rear recombination velocity ( $S_B$ ) set higher
  - Likely due to graded defect density from GaAs/GaSb interface

**TEGa-Better  
minority carrier  
diffusion lengths**



	$L_E$ (nm)	$L_B$ (nm)	$S_E$ (cm/s)	$S_B$ (cm/s)
TEGa 2000 nm Buffer	20	693	$\gg 10^6$	$\gg 10^6$
TMGa 900 nm Buffer	14	310	$\gg 10^6$	$\gg 10^6$

Emitter thickness=125 nm, n-type

Base thickness=1000 nm, p-type

- GaSb solar cells were grown via MOCVD, fabricated, and tested all at RIT
- Homoepitaxial cell demonstrating  $V_{oc}=269$  mV, approaching goal of 360 mV
- IMF cell demonstrating  $V_{oc}=180$  mV, becoming viable for a triple junction
- TEGa appears to be the optimal precursor
- IMF TMGa Illuminated IV does not present a clear story
- High  $S_B$  in IMF devices likely due to a graded defect density



ECCS-1509468



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- Salwan Omar
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